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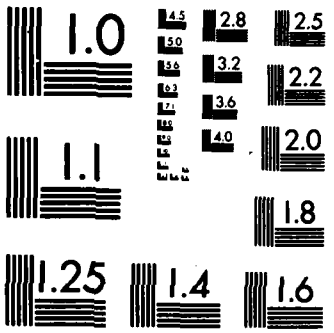

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EMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

novel tunable FIR sources;
hot electron emission in GaAs/GaAlAs heterostructures;
streaming of hot carriers in crossed electric and magnetic fields.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The hot electron temperature of 2D-electrons in GaAs/GaAlAs heterostructures depends linearly on the input power as obtained from FIR emission experiments. Fromsaturation absorption measurements we have obtained for the first time energy relaxation times for 2D electrons in GaAs in high magnetic fields. The streaming of hot carriers in crossed electric and magnetic fields has been observed in p-Ge and n-GaAs. This is a potential concept to obtain a FIR laser.

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"HOT ELECTRON EMISSION IN SEMICONDUCTORS"

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2nd Interim Report
15 January 1985 - 15 June 1985

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"HOT ELECTRON EMISSION IN SEMICONDUCTORS"

2nd Interim Report

15 January 1985 - 15 June 1985

Summary of the Scientific work

The research work on "hot electron emission in semiconductors" was continued with the following topics:

a) Electron heating in GaAs/GaAlAs single heterostructures

b) The emission due to the interaction of drifting carriers in GaAs/GaAlAs heterostructures with a periodic grating

c) FIR emission due to streaming of hot carriers in crossed electric and magnetic fields in p-Ge and n-GaAs

d) FIR saturation spectroscopy on GaAs/GaAlAs heterostructures

ad a) The work on electron heating in high and low mobility GaAs/GaAlAs heterostructures has been completed and published in Applied Physics Letters /1/ (reprint enclosed).

ad b) The work on FIR emission from periodically accelerated motion ("Smith-Purcell-effect") was continued on high mobility GaAs/GaAlAs heterostructures. At present we have not obtained any significant results since the processing of samples is very difficult. We have just recently finished the construction of a reactive ion-etching station which enables us to produce grating structures down to 0.2 µm periodicity. The first modulated samples have just been finished and will be investigated in the near future.

ad c) Further investigation on streaming and accumulation of hot carriers in p-Ge have been performed. The accumulation and probably population inversion of light holes was clearly observed in current measurements and by detecting the emission signal with a Ge:Ga detector. In both cases the signal increased remarkably at a certain value of E/B. The next step will be to prepare a sample with highly parallel surfaces forming a cavity for laser action. Very recently lasing has been reported by Andronov et al. /2/ but not much information is given in their paper. Some experimental problems have to be solved: To achieve high gain the samples have to be rather big which results in a resistance of less than 1Ω after acceptor ionization. It is quite difficult to apply voltages of kV/cm on low impedance samples. A detailed analysis of the emitted spectrum requires the use of InSb and GaAs detectors. Up to now this was prohibited by a strong electric coupling from the high voltage pulse generator to the detector. The use of two separated cryostats for sample and detector respectively will remove this problem.

Additional experiments have been performed on pure n-GaAs (mobility ca. 150.000 cm^2/Vs). Current measurements gave the first evidence for carrier accumulation also in this material. This was the first observation of streaming motion in a III-V semiconductor, in spite of theoretical estimations which predicted a minimum mobility of more than 500.000 cm^2/Vs for achieving streaming /3/.

ad d) High power far infrared spectroscopy is a useful method to determine lifetime of electronic states in semiconductors. In the recent past the lifetimes of Landau- and impurity levels in bulk GaAs and InSb have been measured by saturation of cyclotron and impurity resonance, respectively /4/.

We have performed first cyclotron resonance absorption saturation measurements on GaAs/GaAlAs heterostructures. Saturation is possible in this system due to a sufficient amount of nonparabolicity and polaron contribution to the effective mass. The absorption process is described on the basis on a three level model. By comparison with the experimental data the lifetime is deduced and found to vary from 0.18 to 1.2 ns for samples with decreasing carrier concentration. This indicates the influence of an electron-electron scattering process, similar to that found in bulk material /5/. A detailed description of the process needs more data in the strong saturation regime and also more theoretical work.

M. Helm
R.A. Höpfel
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Electron heating and free-carrier absorption in GaAs/AlGaAs single heterostructures

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We observe far infrared broadband emission from the hot two-dimensional electron plasma in GaAs/AlGaAs single heterostructures grown by molecular beam epitaxy. The radiation is analyzed in two different frequency regimes (around 35 and 100 cm^{-1}). From the relative dependence of the intensities on the applied longitudinal electric field the hot-electron temperatures are determined. From the absolute emission intensities values of the free-carrier absorption coefficient (down to 10^{-5} in ultrahigh mobility samples) are measured.

The topic of carrier heating in the lateral transport of two-dimensional (2D) systems along semiconductor interfaces and heterojunctions has attracted much interest in the last years, especially due to the applications of these systems for fast field-effect transistors[1] and, recently, for hot carrier and real space transfer devices.[2] There are several theoretical papers[3] on the problem of carrier heating in GaAs/AlGaAs heterojunctions. Two main experimental approaches, namely, hot-carrier photoluminescence[4] and magnetotransport,[5] have been made to measure the carrier distribution function or the carrier temperature, respectively.

In this letter we report on far infrared (FIR) emission experiments that were performed by passing a lateral current through the 2D electron system of GaAs/AlGaAs single heterojunctions. This heats up the carriers to a carrier temperature T. It has been shown in the experiments of Shah *et al.*[4] and in femtosecond studies of the intraband relaxation by Erskine *et al.*[6] that the carriers thermalize very fast to a thermal distribution characterized by the carrier temperature T_e via carrier-carrier interaction within less than 100 fs.[6] Since this is by orders of magnitude less than the energy relaxation time (10^{-10}–10^{-9} s) the carrier system itself represents a system in thermal equilibrium.

The FIR emission therefore can be described by thermodynamical considerations. In equilibrium the spectral emission intensity $I(\omega,T)$ of electromagnetic radiation from a system with temperature T is given by

$$I(\omega,T) = I_{BB}(\omega,T)\,A(\omega), \tag{1}$$

where I_{BB} is the spectral emission intensity of a black body and A is the spectral absorptivity of the system, in a 2D system for normal incidence

$$A(\omega) = \frac{4\,\mathrm{Re}\,F}{|\sqrt{\epsilon}+1+F|^2}, \tag{2}$$

with $F = \sigma(\omega)/\epsilon_0 c$ and ϵ being the dielectric constant of the substrate. A Drude form of the dynamical conductivity $\sigma(\omega)$ in n-Si inversion layers has been confirmed by microwave and FIR transmission experiments by Allen *et al.*[7] up to frequencies of 40 cm^{-1}. This allowed the determination of T from the absolute FIR emission intensity at one frequency as shown in Ref. 8. In GaAs/AlGaAs heterostructures, however, the free-carrier absorption has not been measured yet. In order to eliminate the unknown free-carrier absorption and, furthermore, to avoid the problem of measuring absolute FIR intensities, a *relative* method is applied in this work. The signals of two FIR detectors (high-purity n-type GaAs at 35 cm^{-1}, Ga-doped Ge around 100 cm^{-1}) are measured as a function of the applied electric field. The signals of the two detectors are evaluated in the following way: at a field E_i (corresponding to a carrier temperature T_i) the detector signal from the nth detector is given by

$$U_{n,i} = \int_0^\infty R_n(\omega)\,A(\omega)\,I_{BB}(\omega,T_i)\,d\omega. \tag{3}$$

The detector responsivity $R_n(\omega)$ can be written as $R_n(\omega) = R_n^0\,r_n(\omega)$ as well as $A(\omega)$ as $A(\omega) = A_n^0\,a_n(\omega)$. This means that the responsivity $R_n(\omega)$ and the absorptivity of the electron system $A(\omega)$ are mathematically expressed by a product of the relative frequency dependent functions $r_n(\omega)$, $a_n(\omega)$ and absolute factors A_n^0 and R_n^0 at the detector peak frequencies. The following assumptions can be made. (a) A Drude-type relative frequency behavior of $a_n(\omega)$ within the frequency interval of each detector n is assumed, which is a good approximation even if the dynamical conductivity deviates from Drude behavior over a wide range of frequency. (b) The field dependence of $A(\omega)$ is assumed to follow the field dependence of the momentum relaxation time τ via the dynamical conductivity. This change of the dynamical conductivity plays a role at high electric fields where the mobility changes with electric field. Then Eq. (3) contains two unknown parameters, namely, the carrier temperature T_i and the product $A_n^0\,R_n^0$, since the relative detector response $r_n(\omega)$ is well known.[9] Measuring the detector signals $U_{n,i}$ of the two detectors with two different applied electric fields, gives a numerically soluble set of four equations for the four unknown variables. Measurements at more values of the electric field yield more data than unknown variables and thus allow us to prove the consistency of the assumptions. Thus a determination of the electron temperature can be made from the relative emission signals, without knowing the absolute detector response and the optical properties of the system.

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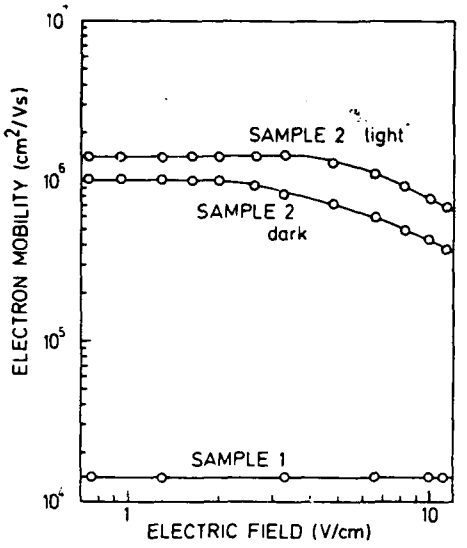

FIG. 1. Carrier mobility as a function of lateral electric field for the two samples: the high mobility sample (sample 2) is measured before (dark) and after (light) illumination with visible light.

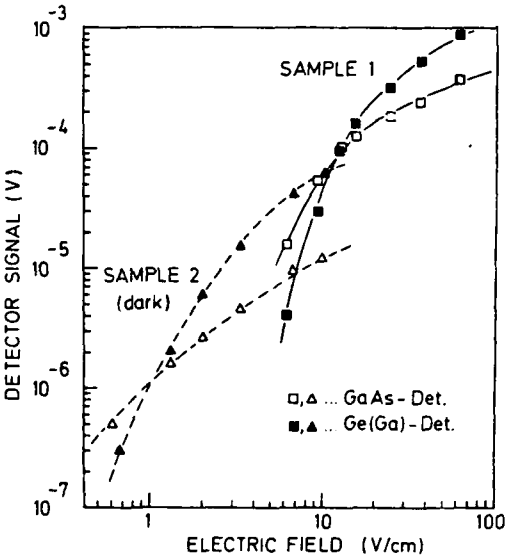

FIG. 2. Detector signals as a function of applied electric field for two samples (sample 1 and sample 2, dark) and two different detectors: GaAs detects the radiation of longer wavelength (35 cm^{-1}) than Ge (Ga) (around 100 cm^{-1}, full symbols).

The samples used in the experiments are modulation-doped $GaAs/Al_{0.35}Ga_{0.65}As$ single heterostructures grown by molecular beam epitaxy. The electron mobilities are 1.0×10^6 cm^2/Vs at electron concentration $n_s = 2.4\times10^{11}$ cm^{-2} at 4.2 K (sample 2). By illumination the electron concentration and mobility can be changed persistently to $n_s = 3.8\times10^{11}$ cm^{-2} and $\mu = 1.3\times10^6$ cm^2/Vs as a consequence of the persistent photoeffect found by Störmer *et al.*[10] Ohmic contacts, which must be of extremely low resistance in order to avoid FIR emission from the contacts, were made by alloying evaporated Au/Ge films of 1000-Å thickness at 400 °C. For comparison also a low mobility sample (1) with $n_s = 8.7\times10^{11}$ cm^2/Vs and $\mu = 1.6\times10^4 cm^2/Vs$ was used. All experiments were performed at liquid helium temperatures. The electric field was pulsed in order to avoid sample heating and to allow the use of correlation techniques. The current through the device and the detector signals are measured simultaneously. The geometry of the waveguide and the detectors favors the detection of the radiation emitted in the direction normal to the surface of the sample. The radiating area is 2 mm × 3 mm.

Figure 1 displays the carrier mobility of both samples as a function of the longitudinal electric field. With increasing electric field the mobility of sample 2 decreases due to electron heating and increased phonon scattering. The low mobility sample (1) does not show a significant field dependence of the mobility since it is dominated by impurity scattering. In Fig. 2 the obtained values of the detector signals as a function of the applied electric field are plotted. Here the characteristic feature of this experiment can be seen very clearly: the signals of the two detectors have remarkably different *slopes*, the increase of the Ge(Ga) detector signal (full symbols) with electric field is much stronger than that of the GaAs detector signals. This is a consequence of the exponential dependence of the Bose quantum statistics on the quantity $\hbar\omega/k_B T$. Therefore, at different frequencies the temperature dependence of the emission intensity is different.

From Eqs. (1)–(3) quantitative values of the electron temperature are determined using numerical fitting procedures. The results are shown in Fig. 3, where the electron heating $\Delta T = T - 4.2$ K is plotted versus the input power per electron: the electron heating increases with the input power and reaches 100 K when the input power exceeds 10^7 eV. s^{-1} per electron. The values of heating for the three different values of carrier concentration and mobility are surprisingly close together, although the electron concentration varies by a factor of 3 and the mobility by a factor of 100. Also the slopes of the curves are similar except sample 2 (light) which shows a somewhat stronger increase of heating with input power. The change of slope, however, is too weak and almost within the error bars, so there can be no conclu-

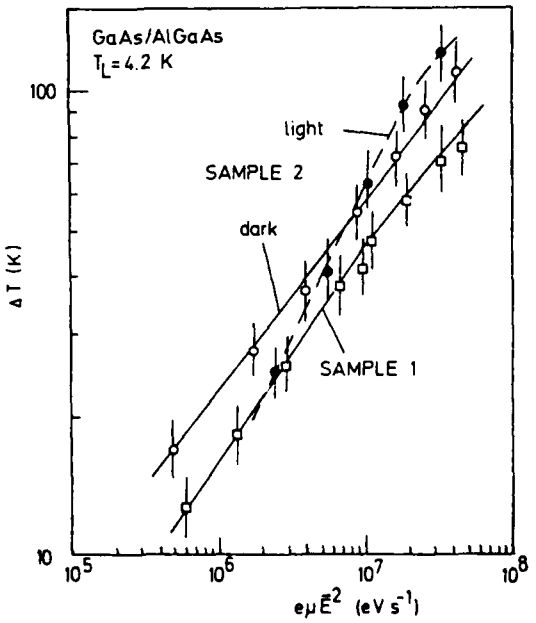

FIG. 3. Electron heating $\Delta T = T - 4.2$ K as obtained from the evaluation of the emission intensities at the two frequencies of the detectors. The abscissa is the input power per electron. The lines (dashed for sample 2 light) are drawn only to guide the eye.

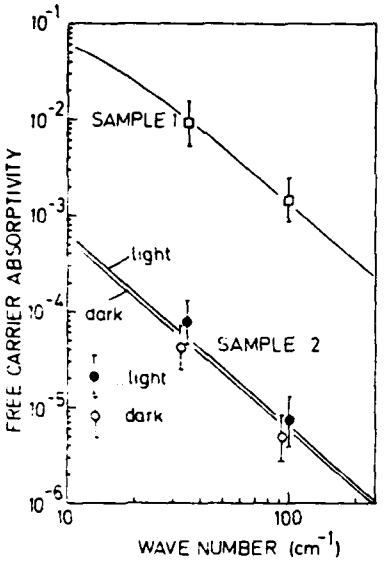

FIG. 4. Measured values of the free-carrier absorptivity vs far infrared wave number. The full curve is calculated assuming Drude behavior with momentum relaxation times taken from the dc mobility.

sions drawn from this behavior. These results show that the heating in GaAs/AlGaAs heterostructures in this range of lattice temperature and carrier heating is a function of the input power per carrier rather than an explicit function of carrier density and mobility. This observation is similar to the results obtained in Si MOSFET's[8] and is also consistent with magnetoconductivity data of Sakaki *et al.*[5] showing also only a small dependence on carrier concentration and mobility. This behavior is expected when acoustic phonon scattering determines the energy loss of the carriers to the lattice.[5,11] The absolute values obtained by this optical emission method are in good quantitative agreement with the results of photoluminescence experiments by Shah *et al.*[4] at high electron temperatures and the values obtained by Sakaki *et al.*[5] from magnetoconductance measurements at low electric fields.

A comparison of the detector signals with those of *n*-InSb cyclotron emission at saturation electron temperatures[12] allows an absolute determination of the emission intensity as described in Ref. 8. Detector responsivities of $\sim 1\times 10^7$ V/W (GaAs) and $\sim 2\times 10^7$ V/W (Ge) with an accuracy of 30% are obtained for the used detectors. The emitted power from the GaAs/AlGaAs heterostructures therefore ranges from 10^{-14} W, which represents the noise level of the detector arrangement, up to 10^{-10} W within the detector intervals. Knowing the absolute emission intensity and the electron temperature, we can separate the product $A_n^0 R_n^0$ and give values of the absorptivity of the 2D carrier system at the detector frequencies. The results are shown in Fig. 4. The absorptivity of the carrier plasma is plotted for the different samples at the two detector frequencies. The free-carrier absorption (evaluated for low electric fields) strongly depends on the carrier mobility; the absorption varies by two orders of magnitude from the low mobility sample (high absorptivity = emissivity) to the high mobility sample which reveals a very low absorptivity of below 10^{-5} at 100 cm^{-1}. Note that these low values of absorption are measurable without gate modulation techniques as usually applied for absorption measurements in 2D systems.[7] The full curve in Fig. 4 displays the theoretical frequency and mobility dependence assuming Drude conductivity with the values of the relaxation time τ taken from the dc mobility. The agreement (within the experimental error range coming from the uncertainty in measuring the absolute detector responsivity) obviously shows that the FIR absorption in the 2D plasma is determined by the same scattering processes as the dc transport. This means that Coulomb scattering by residual impurities, which is the dominant scattering process in these structures, also provides the momentum transfer for the free-carrier optical transitions.

In conclusion, we have observed broadband far infrared radiation from the hot-carrier plasma in GaAs/AlGaAs heterojunctions with ultrahigh as well as low electron mobility. A relative method of determining the carrier heating in the electric field is introduced, which allows the measurement of T over a wide range of carrier heating ($10\,\mathrm{K} < T < 150\,\mathrm{K}$). The method can be also applied to investigate carrier heating in small devices and integrated circuits. At room temperature, however, one has to work in the near infrared range in order to obtain a similarly strong dependence of the emission intensity on carrier heating. Furthermore, the FIR absorption of the 2D plasma could be estimated for the first time, showing a strong dependence on the amount of impurity scattering which permits the momentum transfer for the optical transition.

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